

Waves, Bubbles, Noise and Underwater Communications

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LONG-TERM GOALS

There are 3 long-term goals. The first is to measure and model the effects of near-surface bubbles on the generation, scattering and attenuation of sound during breaking wave conditions. Ultimately, the goal is to develop predictive algorithms for surface scattering conditions from measurements of the wind-generated ambient noise field. The second long-term goal is to measure, model and exploit focused acoustic arrivals that occur on short length scales beneath sea swell and study their impact on underwater communications systems in littoral and near-shore regions. The third long-term goal, to understand the physical mechanisms responsible for the Knudsen spectrum for wind-driven underwater ambient noise, has been achieved.

OBJECTIVES

Work over the past 12 months has focused on 2 main objectives, which have been to (1) analyze the Surface Processes and Communications Experiment (SPACE08) data collected as part of the field expedition at the WHOI Coastal Observatory during fall of 2008, and (2) finish the analysis of the physical origin of the Knudsen spectrum. The first data analysis objective has been to create quality reports and overview summaries of the data collected during the SPACE08 experiment, and begin a comparison with the data streams provided by other investigators. A secondary objective has been to work with Dr. James Preisig at WHOI to understand the connection between the statistical distribution of forward scattered energy from surface gravity waves on short length scales and the statistical properties of the wave field.

APPROACH

The underlying approach for all objectives is similar: mathematical and physical models are developed for the processes under study (wave noise or forward scattering of sound by surface gravity waves, for example), and these are tested against data collected in controlled laboratory experiments and then used to understand observations from ocean experiments, which form an integral part of the work.

Wave noise modeling. The approach to understanding wave noise has been to identify and model the individual physical mechanisms resulting in bubble production in breaking waves and the hydrodynamical mechanism stimulating the production of sound by newly-formed bubbles. These are then measured directly in laboratory experiments that couple acoustic recordings with physical measurements of turbulence and bubble size distributions. The final model is compared with the Knudsen spectrum from open-ocean data sets.

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Surface Scattering by gravity waves. The approach here has been to collaborate with Dr. Chris Tindle at the University of Auckland, New Zealand to develop a range-dependent propagation model that can handle surface gravity waves and bubbles and Dr. Jim Preisig at Woods Hole Oceanographic Institution to create an analytical model that relates scattered arrival amplitudes to the properties of the surface wave field. Scattering from the sea surface over short propagation ranges (a few hundred meters) involves only a few reflection points resulting in long-tailed, non-Gaussian for the probability density distribution of the arrival amplitude. Dr. Preisig is the driving force behind the PDF calculations. Jim is comparing the results with data from a scale-model tank experiment we did together with Chris Tindle in 2008, and will be compared with data from experiments in the littoral zone to study gravity wave focusing.

Near-surface bubble effects on sound scattering. This work is in its early stages, with data becoming available from the SPACE08 experiment conducted during the fall of 2008 at WHOI (Chief Scientist: Dr. Jim Preisig) in partnership with Dr. Andone Lavery from WHOI, myself and Dr. Dale Stokes from SIO, Dr. David Farmer from URI, Dr. Burkard Baschek from UCLA and Dr. Svein Vagle from IOS, BC. Video footage of whitecaps made from the Martha's Vineyard Coastal Observatory Air-Sea Interaction Tower is being analyzed for fractional whitecap coverage by Dr. Adrian Callaghan in Ireland. This data will be combined with underwater recordings of ambient noise to infer statistics of the space and time-varying distributions of bubble populations at the sea surface. These will be used with the Wavefronts propagation model to study the effects of bubbles on the communications transmissions at different wind speeds and sea states through the SPACE08 experiment. The results of this modeling study will be combined with the actual transmission data from SPACE08 to test our understanding of the forward scatter amplitude statistics from the surface-reflected arrival.

WORK COMPLETED

The Surface Processes and Acoustic Communications Experiment (SPACE08). As discussed in the 2008 performance report, the SPACE08 experiment was conducted during the fall of 2008 at the WHOI Air-Sea Interaction Tower. An underwater video camera housed on a surface-following frame imaged bubbles within breaking whitecaps. A magnetic-coil conductivity cell used to detect high void fractions of air and trigger the camera during the passage of a wave over the instrument also provided a time-series of conductivity 20-40 cm below the ocean surface. An array of 4 hydrophones mounted on the seafloor recorded 42-minute segments of ambient noise every 2 hours during the experiment. Surface gravity waves and tides were measured with an array of 3 capacitance gauges 11 meters long mounted on a beam 4 meters below the water surface. This array provided information about the short-wavelength surface gravity wave spectrum. The surface wave field was also measured with two Falmouth Scientific Instruments 3D wave gauges mounted on the sea floor. One of these instruments was co-located with a multi-frequency upward-looking sonar deployed by Andone Lavery, which enabled us to compare surface elevation time series recorded by the 3D wave with elevation estimates from the sonar. Surface conditions were monitored with a 5 MPixel video camera mounted on the top of the Air-Sea Interaction Tower, which captured between 4-7 frames per second. Jim Preisig, Andone Lavery, David Farmer and I met at WHOI for a week in September this year to begin analyzing the SPACE08 data and integrating the environmental measurements with the communications transmissions. In addition to the SPACE08 data analysis, a set of surface images taken during the

SPACE02 deployment was analyzed by Dr. Adrian Callaghan for whitecap coverage as a function of wind speed and sea state.

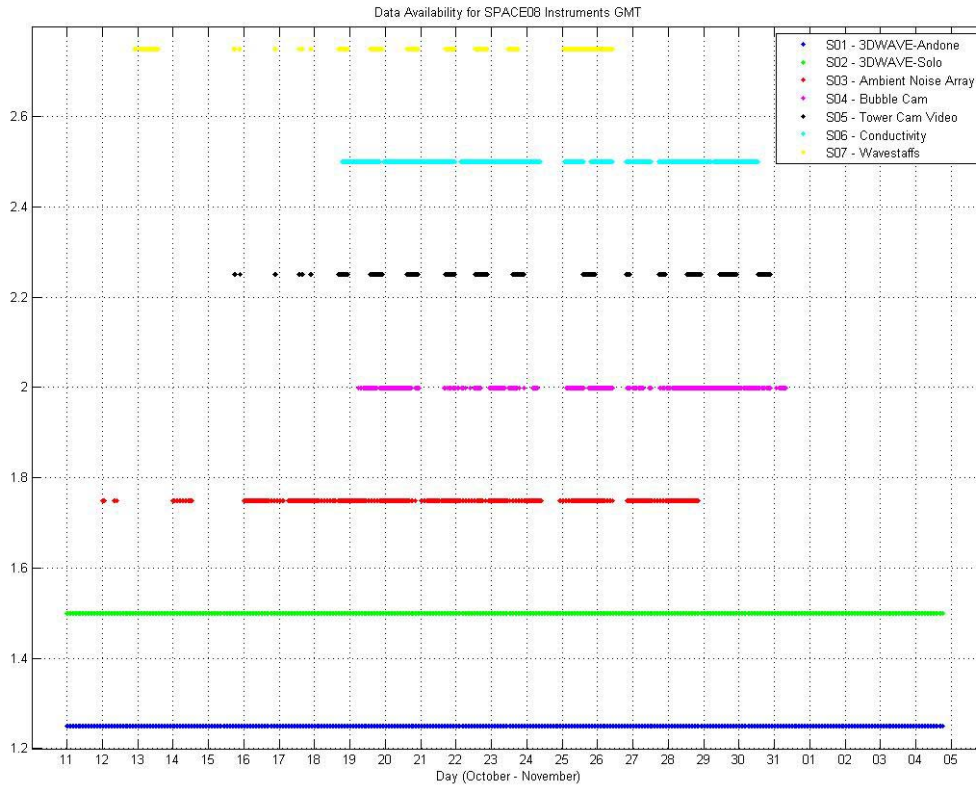


Figure 1. A summary of Scripps instrumentation availability during the 31/2 weeks of the SPACE08 experiment. Some instruments (such as the video camera and the wave staffs) were only run during daylight hours.

Wave Noise Modeling. Multiple performance periods have culminated in a model for the underwater noise radiated by breaking waves. The model is based on models and measurements of bubble creation rates in breaking wave crests as a function of bubble radius, measurements of fluid turbulence with the breaking crest, and a model for the acoustical excitation of newly-formed bubbles. The model has been tested against measurements made in beneath laboratory breaking waves, and can adequately reproduce the absolute spectral level of the noise in addition to the noise spectral roll-off.

Near-surface bubble effects on sound scattering. Two primary tasks have been accomplished in this period on this topic. The first is the addition of range and depth-dependent complex sound speed profiles to the Wavefronts propagation model to account for the attenuation and refraction of sound propagating through bubble plumes. This modification to the Wavefronts model has not yet been tested against laboratory or field data. The second task is the completion of an initial series of scale model tank experiments to provide calibration data with waves and bubbles for the Wavefronts model. Two ITC1089D hydrophones were placed in the glass-walled flume at the SIO hydraulics facility and used to study the forward propagation of high frequency (200 kHz) sound pulses beneath surface gravity waves and through artificially-created bubble plumes made with an array of wood air stones. The size

distribution of the bubbles within the plume was measured and the void fraction of air in the plume was varied by changing the gas flux through the air stones. Transmissions were also made through plumes rising beneath waves, and through the plume of bubble generated at the surface of the flume by a breaking wave packet.

RESULTS

A model of wave noise. This is one of the primary results produced over the last performance period. It is summarized by the equation

$$(1) \quad P(\omega) = \frac{2\pi}{3} \frac{p_0^2}{T} \frac{\beta V}{R^2} \frac{\bar{\lambda} \phi}{\alpha_0 \omega^2},$$

where ω is angular frequency, $P(\omega)$ is the power spectrum of the whitecap noise, measured one meter below the whitecap, p_0 is the peak pressure radiated by individual bubbles at the moment of their creation, T is the duration of active breaking, β represents an adjustment to the bubble cloud volume to account for scattering and absorption of sound by quiescent bubbles within the plume, V is the volume of the bubble plume, R is the distance from the observation point to the center of the plume, $\bar{\lambda}$ is the bubble creation rate during the acoustically phase of wave breaking, which is a function of bubble size and therefore wave noise frequency, $\phi = 20.4$ is a constant relating the natural frequency of the bubble to the bubble's radius, and α_0 is the reciprocal damping time of a bubble with natural frequency ω .

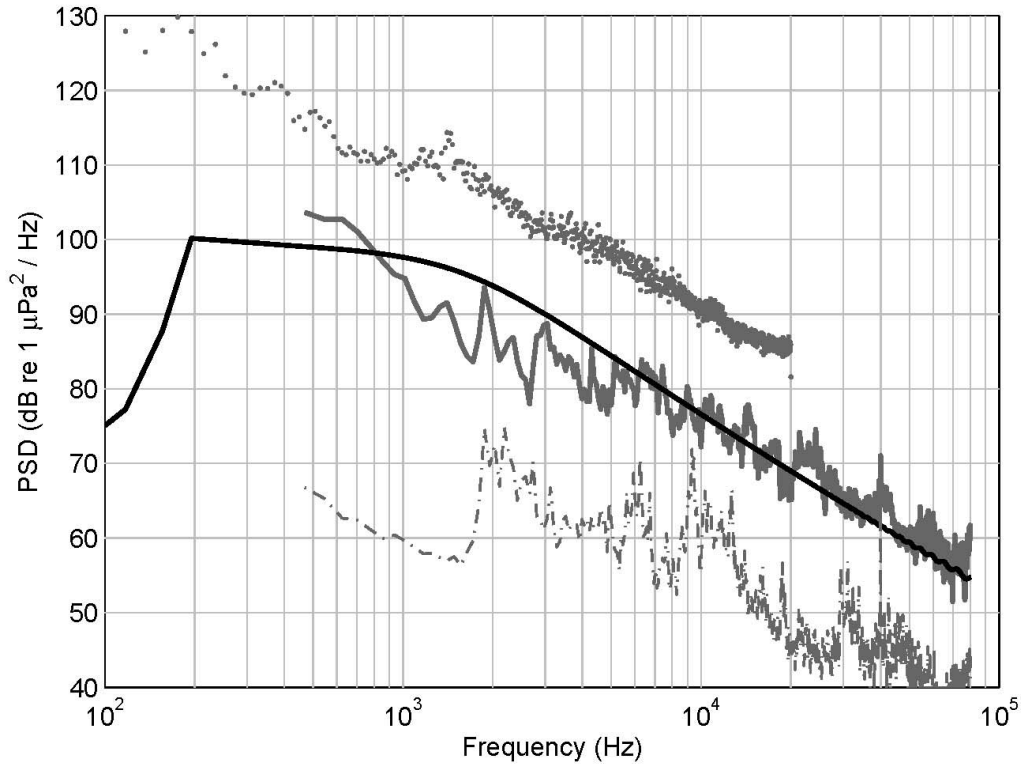


Figure 1. Model calculations of the noise radiated by a breaking wave in a laboratory flume. The solid, black line shows the model results for the wave noise 0.25 m below the breaking wave crest.

The solid grey line shows the wave noise measured 0.25 m below the wave crest. The measured noise levels have been compensated for reverberation in the flume. The grey dash-dot line shows the noise floor in the flume. The grey dots show the power spectral density of an individual white cap measured in the Pacific ocean during a storm 160 km west of Point Conception. For comparison, this curve has been scaled to a distance of 0.25 m below the whitecap.

One of the immediate applications of this model is a calculation of the power law dependence of the Knudsen curves on frequency for ambient oceanic noise in the absence of biological or shipping noise. From equation (1), the power law dependence of the noise spectrum should scale with the bubble creation rate minus the frequency dependence of the damping constant minus 2 (from the ω^2 in the denominator). All other factors are assumed to be frequency-independent. The bubble creation rate scales with frequency $3/2$ and bubble damping scales with frequency $-4/3$. Adding terms yields $n = 3/2 - 4/3 - 2 = -11/6$, which is in close agreement with the generally accepted slope of $-10/6$ for open-ocean ambient noise.

IMPACT/APPLICATIONS

The development of a model for ambient noise has a number of potential applications. One which I am currently pursuing in collaboration with Dr. James Preisig is to use the wave noise model and measurements of the ambient noise to calculate bubble production rates by breaking waves and use these to model surface masking effects that arise when winds are sufficiently strong to induce wave breaking. The ultimate impact will be improved signal processing algorithms for underwater modems.

Other important military and civil applications include characterizing ocean surface scattering, understanding ocean color and optical scattering in the upper ocean boundary layer, building improved models of air-sea gas flux and marine aerosol production.

RELATED PROJECTS

“Underwater Acoustic Propagation and Communications: A coupled research program”, funded under the Multidisciplinary University Research Initiative (MURI) by ONR.

PUBLICATIONS

Callaghan, A.H., G.B. Deane and M.D. Stokes “Observed physical and environmental causes of scatter in whitecap coverage values in a fetch-limited coastal zone” J. Geophys. Res. **113** C05022, doi:10.1029/2007JC004453 (2008).

Tindle, C.T., G.B. Deane and J.C. Preisig, “Reflection of underwater sound from surface waves” J. Acoust. Soc. Am. **125** 66-72 (2009).